

# Final Report: Molecular Beam Assembly (MBA) of Graphene Nanoribbons (GNRs): Synthesis, Transport Study, and Flexible Electronics

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## **INTRODUCTION:**

Since the rise of graphene, it has attracted strong attention due to its exceptional electronic,<sup>1</sup> thermal,<sup>2,3</sup> mechanical,<sup>4,5</sup> and optical properties.<sup>6-8</sup> Due to the lack of an energy bandgap in graphene, electronic applications of graphene have been limited to functionalities where switching off the device is not necessary. Accordingly, technologies such as graphene radio frequency transistors have been drawing lots of attention because it is easily implementable in real life applications.<sup>9-11</sup> On the contrary, digital electronics applications require a sufficient bandgap for the channel material in order to switch off the device for proper operation. As a result, extensive research was done to use graphene as a digital switch by employing novel device structures that made use of the high tunability of graphene Fermi level.<sup>12-16</sup> Although these devices perform fairly well, their structures are complex and lack the use of excellent charge transport properties of graphene. On the other hand, numerous efforts to induce a bandgap in graphene by chemical modification,<sup>17-19</sup> use of multilayer graphene with dual gates,<sup>20-22</sup> and other methods<sup>23</sup> were devoted. Nevertheless, these methods are either difficult to control or devices fail to perform well.

Recently, the narrowing of graphene into stripes with widths ~ 10 nm was studied both theoretically<sup>24</sup> and experimentally<sup>25</sup> to create an energy bandgap in the electronic structure of graphene due to quantum confinement. However, the theoretical predictions and the experimental data did not match due to inability to control edge structures.<sup>26</sup> Consequently, several methods were used to create

GNRs including top down etching of graphene into GNR,<sup>25, 27, 28</sup> unzipping of carbon nanotubes,<sup>29-33</sup> chemically producing GNR,<sup>34-36</sup> bottom-up chemical synthesis,<sup>37-39</sup> and various methods for producing arrays of GNR.<sup>33, 40-45</sup> Additionally, several interesting transport properties were experimentally tested for several types of GNRs.<sup>46, 47</sup> Nevertheless, in order to create a reliable technology that uses GNR as a platform, better control of GNR should be accomplished. And issues like width control, ribbon to ribbon variations, and the quality of the materials have to be precisely and reproducibly controlled. These features are essential to control the electronic characteristics of the devices fabricated and proper operation of complex circuits. In this report, we present our efforts to study the properties of top-down GNRs and bottom-up synthesized GNRs and utilized them in applications such as chemical sensing and thin-film transistors (TFT). For top-down GNRs, we used helium ion beam lithography (HIBL) to create GNR field-effect transistors (GNR FETs) with highly dense GNR arrays with one of the smallest half-pitch GNR reported to date (5 nm). Moreover, we used chemically synthesized GNRs because the controlled widths and edge structures of bottom-up GNRs allow precise control over the electrical and optical properties of GNRs which is important for numerous applications. By studying both long chemically synthesized GNRs and short ones (i.e. nanographenes), we were able to establish new deposition techniques and unique applications for such GNRs. The results presented in this report are first steps to understanding the properties of chemically synthesized GNRs and exploring their potential applications in electronics and sensing.

## **PATTERNING, CHARACTERIZATION AND CHEMICAL SENSING APPLICATIONS OF GRAPHENE NANORIBBON ARRAYS DOWN TO 5 NM USING HELIUM ION BEAM LITHOGRAPHY:**

In this section, we report our results in using HIBL for high resolution patterning of graphene down to 5 nm half-pitch arrays (Figure 1). We were able to control the aspect ratio of the GNRs up to 400 (i.e. the widths and lengths of GNRs are 5 nm and 2000 nm, respectively). These reduced

dimensions are enabled by the small scattering size and the small scattering lengths of helium ion beam. We performed low temperature output characteristic (i.e.  $I_d$ - $V_d$ ) measurements of a device to study the nature of thermionic activation of carriers through the graphene/GNR junction. For this device, GNRs with a width of 5 nm and length of 200 nm were patterned. Figure 2 shows the temperature dependence of the  $I_d$ - $V_d$  curves with clear reduction of the conductance as the temperature is reduced. The nonlinearity of the differential conductance near the zero bias point (i.e.  $V_d = 0$  V) is clearly shown for lower temperatures in Figure 2b. This effect indicates a potential barrier created for carriers transporting through graphene/GNR junction. Moreover, estimation of the activation energy (EA) was carried out using the minimum conductance value for each temperature point. Figure 2c shows that the minimum conductance ( $G_{min}$ ) points fit with the thermally activated carriers' equation:

$$G_{min} = G_1 e^{\frac{-E_A}{K_B T}}$$

Where  $G_1$  is a constant,  $K_B$  is Boltzmann's constant,  $T$  is the absolute temperature, and  $E_A$  is the activation energy. The curve fitting yielded an  $E_A$  of 44 meV and the GNR bandgap ( $E_G$ ) is therefore estimated to be  $> 88$  meV. Finally, we measured the sensitivity of GNR arrays to  $NO_2$  gas and observed ppb level sensitivity, which shows the potential for using HIBL GNR arrays for sensing applications.

## **DEPOSITION, CHARACTERIZATION, AND THIN-FILM-BASED CHEMICAL SENSING OF ULTRA-LONG CHEMICALLY SYNTHESIZED GRAPHENE NANORIBBONS:**

In this section we report optimized conditions for deposition and visualization of individual bottom-up chemically synthesized GNRs and films on Si/SiO<sub>2</sub> substrates (Figure 3), and their applications as devices and chemical sensors. We have studied different annealing conditions and their effect on GNR thin-film devices using attenuated-total-reflectance Fourier-transform infrared

spectroscopy (ATR-FTIR), electrical measurements and Raman spectroscopy which revealed the enhanced conductivity of GNR films after annealing due to the dodecyl side chains removal. AFM of individual deposited GNRs revealed GNRs with a length of >500 nm and a thickness of  $\sim 0.78$  nm. Additionally, Raman spectroscopy of individual deposited GNRs showed characteristic D, G, 2D, and D+D' peaks and electrical measurements on an individual GNR confirmed the conductivity of such GNRs. Finally, we have demonstrated an application of the GNR thin-film devices by measuring the sensitivity of such GNRs to NO<sub>2</sub> gas and observed ppb level sensitivity, highlighting the potential for using chemically synthesized GNRs for cost-conscious and scalable sensing applications. Our GNR film sensors exhibit high sensitivities comparing favorably to other graphene-based NO<sub>2</sub> sensors. We observed  $\Delta G/G_0$  of  $\sim 5.6\%$  for NO<sub>2</sub> concentration of 50 ppb. We attribute this enhanced NO<sub>2</sub> sensitivity to the semiconducting nature of chemically synthesized GNRs which allows higher level of current modulation *via* adsorption of NO<sub>2</sub> molecules than semimetal pristine graphene. Additionally, compared to graphene, edges of GNRs are more chemically active than pristine Sp<sup>2</sup> surface of graphene which might play an important role in the molecular adsorption and sensing mechanisms. In the future, it may be beneficial to study the sensing performance of GNRs of different width and length to understand the mechanisms behind the high sensitivity of GNR NO<sub>2</sub> sensors.

## **VAPOR-PHASE TRANSPORT DEPOSITION, CHARACTERIZATION, AND APPLICATIONS OF LARGE NANOGRAPHENES:**

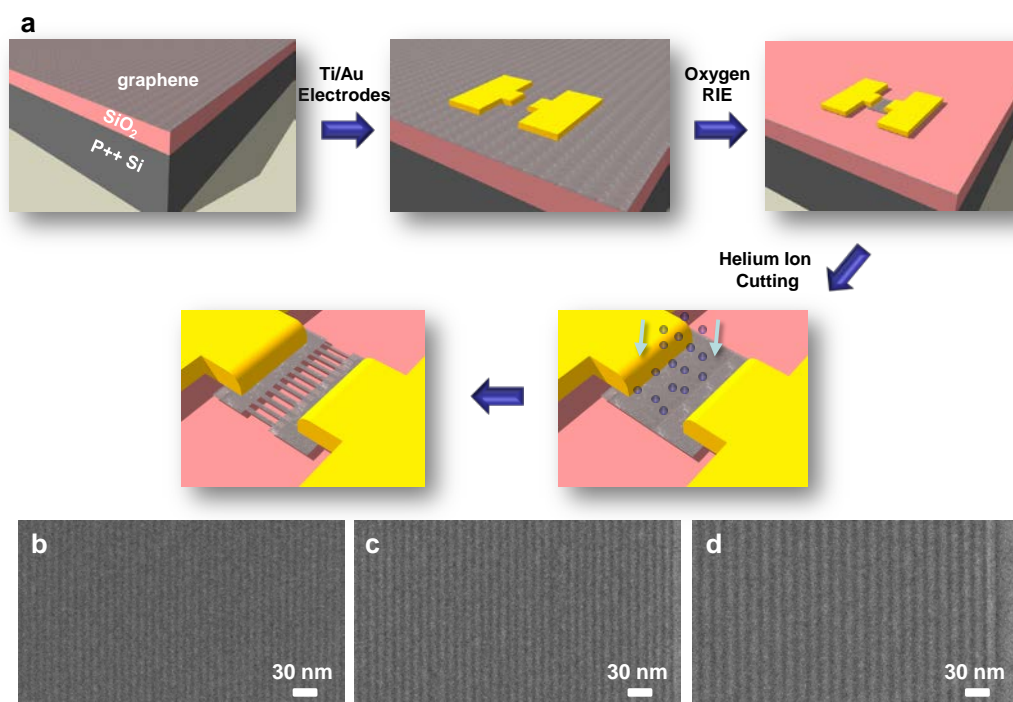
In this section, we report our finding that films of large nanographene molecules can be prepared using vacuum sublimation without destroying their aromatic core structures. Specifically, we developed a vapor-phase transport (VPT) approach, in which the large nanographene molecules are sublimated on a substrate in a vacuum-sealed glass tube. These films comprise of stacked large nanographene molecules maintaining their aromatic cores, without fusion or fragmentation. FETs based on such films exhibited current on/off ratios in the range of 140 – 170. We chose two kinds of

large nanographene molecules which have been considered to be too large for vacuum sublimation (Figure 4). We used atomic force microscopy (AFM), matrix-assisted laser desorption/ionization time-of-flight mass spectrometry (MALDI-TOF MS), and Raman spectroscopy to characterize the film morphology, to compare the pristine material with the sublimated films, and to ensure that the deposited large nanographenes in the films maintained their basal plane structures. The results showed that the basal plane of large nanographenes can be maintained under the conditions we have used. Moreover, we showed that graphene nanopatch (GNP) and C<sub>96</sub> films (Figure 4) can be used in the fabrication of thin-film transistors (TFT) with improved current on/off ratios by sublimating the molecules of choice onto substrates with prefabricated electrodes (Figure 5). Besides the observation of uniform films, we have also observed crystal-like island structures upon sublimation of GNPs, which have shown even higher electrical conductance than the films. The GNP crystal TFT demonstrated a field-effect mobility of  $\sim 1 \text{ cm}^2/\text{V.s}$ , which can be further improved by improving the contact resistance and the thickness of the crystal. Our VPT approach to prepare pristine nanographene molecular films suggest great promise for the future implementation of large nanographenes in electronic, optoelectronic and sensing applications.

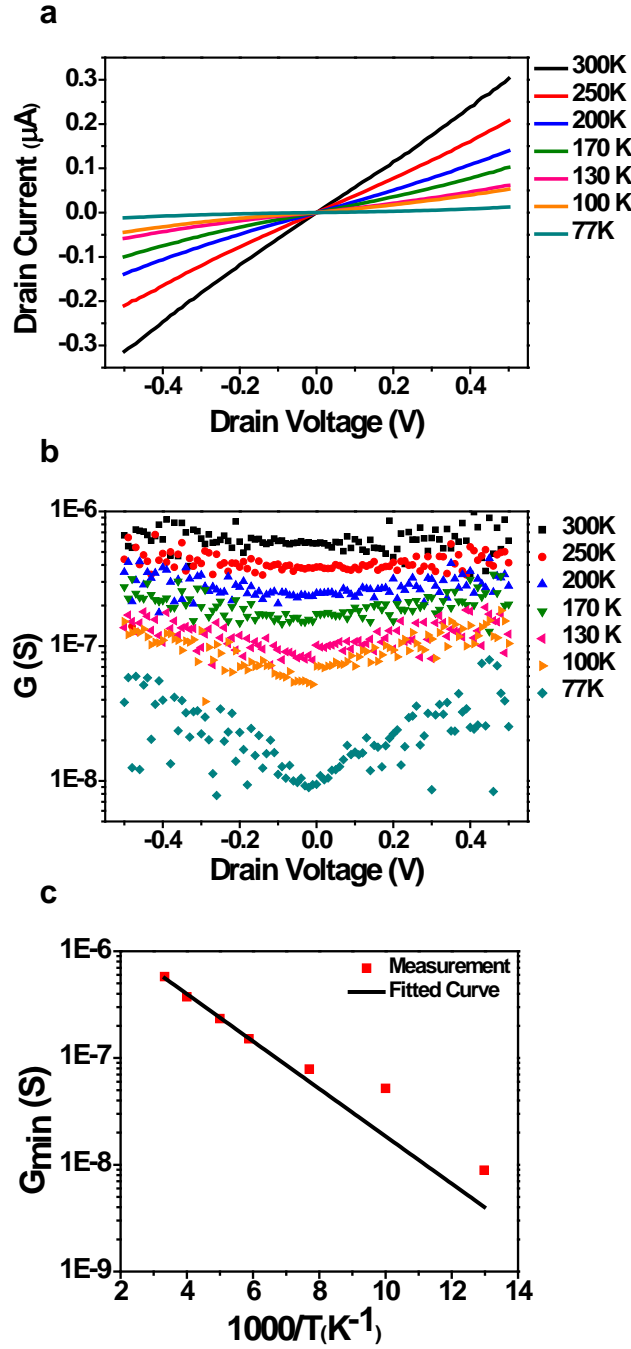
## **SUMMARY:**

In summary, we have studied three different types of GNRs in this project. First, we examined the potential for using HIBL to pattern narrow and aligned GNRs. We have successfully patterned 5 nm half-pitch GNRs, which is the smallest pitch reported to date. Then, we studied ultra-long (500 nm) chemically synthesized GNRs. We were able to deposit individual GNRs, and films of such GNRs and characterize their electrical, optical and chemical sensing properties. Finally, we developed a vapor-phase transport technique to create films of chemically synthesized large nanographene molecules. We have successfully fabricated TFTs based on such films and showed the potential of crystalizing such molecules for high performance TFTs.

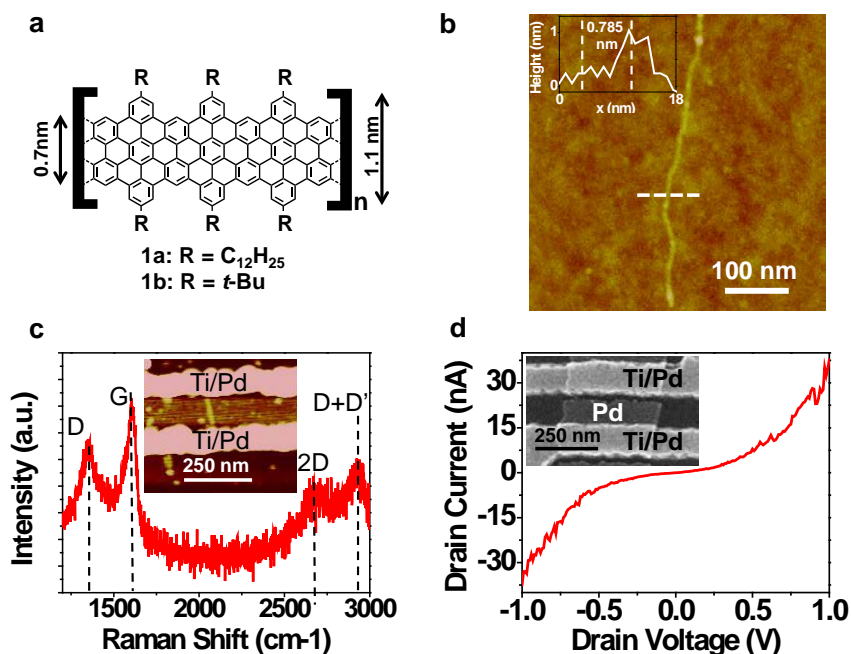
## FIGURES:



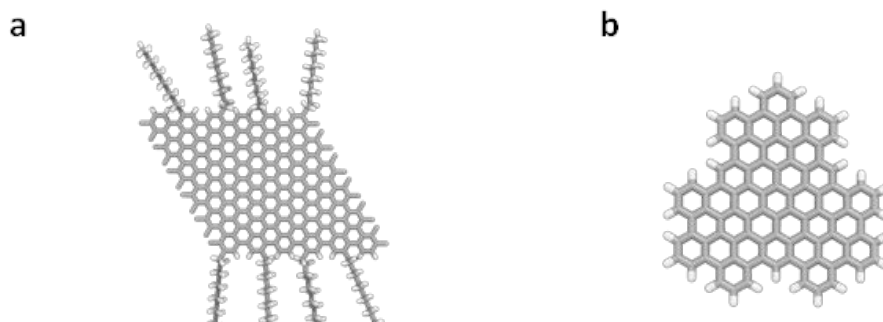
**Figure 1.** a) Scheme of GNR array devices fabricated by HIBL. b, c, d) Helium ion microscope images of 5nm, 6nm and 7.5 nm half-pitch arrays.



**Figure 2.** Temperature-dependent electrical measurements of 5nm wide and 200 nm long GNR array: a) Output characteristics of the device under different temperatures. b) Minimum differential conductance ( $G_{\min}$ ) variation *versus* drain voltage at different temperatures. c) Minimum conductance *vs.* inverse temperature and the corresponding curve fitting. The gate voltage was 0V.

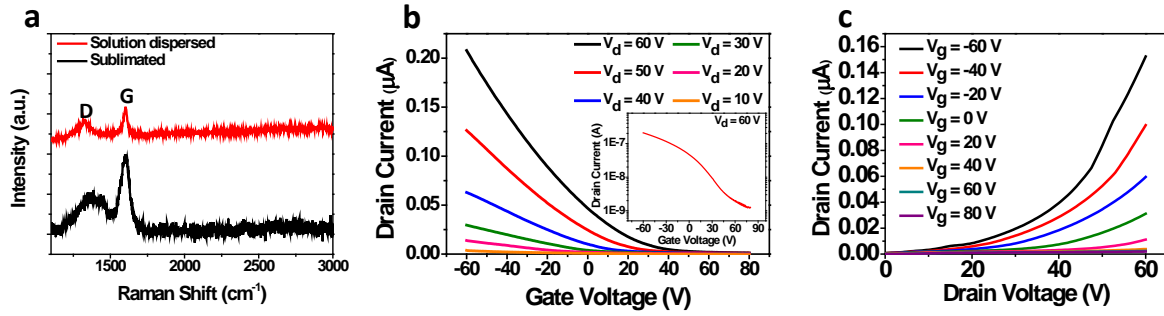


**Figure 3.** a) Chemical structure of GNRs **1a** and **1b**. b) AFM tapping mode height image revealing synthesized GNR length > 500 nm. Inset showing a height profile of the GNR (at the dashed line) revealing a height of 0.785 nm. c) Raman spectrum of an individual GNR revealing D, G, 2D and D+D' bands. Inset shows an individual GNR between two Ti/Pd electrodes. d) Current vs. drain voltage ( $I-V_d$ ) characteristic of an individual GNR device after metal angle deposition with a channel length of  $\sim 20$  nm. Inset showing an SEM image of a 20 nm gap between Ti/Pd and angle-deposited Pd.



**Figure 4.** Molecule structure, vapor-phase transport deposition, and characterization of the nanographene molecules. **a)** Molecule structure of graphene nanopatch (GNP) (dangling bonds at edges indicate longitudinal repeat of such structure). **b)** Molecular structure of  $C_{96}$  molecules used in this study. Carbon and hydrogen atoms are represented in grey and white respectively





**Figure 5. a)** Raman spectra of GNP films prepared by liquid-phase processing and sublimation. **b)**  $I_d$ - $V_g$  characteristics of a GNP film TFT at different drain biases. Inset shows a logarithmic scale  $I_d$ - $V_g$  curve of GNP film TFT showing a current on/off ratio of  $\sim 174$ . **c)**  $I_d$ - $V_d$  characteristics of the GNP film TFT at different gate voltages showing highly non-linear curves indicating a Schottky contacted TFT.

## REFERENCES AND NOTES:

1. Novoselov, K. S.; Geim, A. K.; Morozov, S. V.; Jiang, D.; Zhang, Y.; Dubonos, S. V.; Grigorieva, I. V.; Firsov, A. A., Electric Field Effect in Atomically Thin Carbon Films. *Science* **2004**, *306*, 666-669.
2. Balandin, A. A., Thermal Properties of Graphene and Nanostructured Carbon Materials. *Nat. Mater.* **2011**, *10*, 569-581.
3. Balandin, A. A.; Ghosh, S.; Bao, W.; Calizo, I.; Teweldebrhan, D.; Miao, F.; Lau, C. N., Superior Thermal Conductivity of Single-Layer Graphene. *Nano. Lett.* **2008**, *8*, 902-907.
4. Kim, K. S.; Zhao, Y.; Jang, H.; Lee, S. Y.; Kim, J. M.; Kim, K. S.; Ahn, J.-H.; Kim, P.; Choi, J.-Y.; Hong, B. H. *et al*, Large-Scale Pattern Growth of Graphene Films for Stretchable Transparent Electrodes. *Nature* **2009**, *457*, 706-710.
5. Lee, C.; Wei, X.; Kysar, J. W.; Hone, J., Measurement of the Elastic Properties and Intrinsic Strength of Monolayer Graphene. *Science* **2008**, *321*, 385-388.
6. Yan, H.; Low, T.; Zhu, W.; Wu, Y.; Freitag, M.; Li, X.; Guinea, F.; Avouris, P.; Xia, F., Damping Pathways of Mid-infrared Plasmons in Graphene Nanostructures. *Nat. Photonics.* **2013**, *7*, 394-399.
7. Emani, N. K.; Chung, T.-F.; Ni, X.; Kildishev, A. V.; Chen, Y. P.; Boltasseva, A., Electrically Tunable Damping of Plasmonic Resonances with Graphene. *Nano Lett.* **2012**, *12*, 5202-5206.
8. GuT; PetroneN; McMillan, J. F.; van der Zande, A.; YuM; Lo, G. Q.; Kwong, D. L.; HoneJ; Wong, C. W., Regenerative Oscillation and Four-Wave Mixing in Graphene Optoelectronics. *Nat. Photonics.* **2012**, *6*, 554-559.
9. Liao, L.; Lin, Y.-C.; Bao, M.; Cheng, R.; Bai, J.; Liu, Y.; Qu, Y.; Wang, K. L.; Huang, Y.; Duan, X *et al*, High-speed Graphene Transistors with a Self-Aligned Nanowire Gate. *Nature* **2010**, *467*, 305-308.
10. Badmaev, A.; Che, Y.; Li, Z.; Wang, C.; Zhou, C., Self-Aligned Fabrication of Graphene RF Transistors with T-Shaped Gate. *ACS Nano* **2012**, *6*, 3371-3376.
11. Lin, Y.-M.; Dimitrakopoulos, C.; Jenkins, K. A.; Farmer, D. B.; Chiu, H.-Y.; Grill, A.; Avouris, P., 100-GHz Transistors from Wafer-Scale Epitaxial Graphene. *Science* **2010**, *327*, 662.
12. Britnell, L.; Gorbachev, R. V.; Jalil, R.; Belle, B. D.; Schedin, F.; Mishchenko, A.; Georgiou, T.; Katsnelson, M. I.; Eaves, L.; Morozov, S. V. *et al*, Field-Effect Tunneling Transistor Based on Vertical Graphene Heterostructures. *Science* **2012**, *335*, 947-950.
13. Yang, H.; Heo, J.; Park, S.; Song, H. J.; Seo, D. H.; Byun, K.-E.; Kim, P.; Yoo, I.; Chung, H.-J.; Kim, K. *et al*, Graphene Barristor, a Triode Device with a Gate-Controlled Schottky Barrier. *Science* **2012**, *336*, 1140-1143.
14. Georgiou, T.; Jalil, R.; Belle, B. D.; Britnell, L.; Gorbachev, R. V.; Morozov, S. V.; Kim, Y.-J.; Gholinia, A.; Haigh, S. J.; Makarovskiy, O. *et al*, Vertical Field-Effect Transistor Based on Graphene-WS<sub>2</sub> Heterostructures for Flexible and Transparent Electronics. *Nat. Nanotechnol.* **2012**, *8*, 100-103.
15. Zeng, C.; Song, E. B.; Wang, M.; Lee, S.; Torres, C. M.; Tang, J.; Weiller, B. H.; Wang, K. L., Vertical Graphene-Base Hot-Electron Transistor. *Nano. Lett.* **2013**, *13*, 2370-2375.
16. Yu, W. J.; Li, Z.; Zhou, H.; Chen, Y.; Wang, Y.; Huang, Y.; Duan, X., Vertically Stacked Multi-Heterostructures of Layered Materials for Logic Transistors and Complementary Inverters. *Nat. Mater.* **2012**, *12*, 246-252.
17. Elias, D. C.; Nair, R. R.; Mohiuddin, T. M. G.; Morozov, S. V.; Blake, P.; Halsall, M. P.; Ferrari, A. C.; Boukhvalov, D. W.; Katsnelson, M. I.; Geim, A. K. *et al*, Control of Graphene's Properties by Reversible Hydrogenation: Evidence for Graphane. *Science* **2009**, *323*, 610-613.
18. Balog, R.; Jorgensen, B.; Nilsson, L.; Andersen, M.; Rienks, E.; Bianchi, M.; Fanetti, M.; Laegsgaard, E.; Baraldi, A.; Lizzit, S. *et al*, Bandgap Opening in Graphene Induced by Patterned Hydrogen Adsorption. *Nat. Mater.* **2010**, *9*, 315-319.
19. Chang, C.-K.; Kataria, S.; Kuo, C.-C.; Ganguly, A.; Wang, B.-Y.; Hwang, J.-Y.; Huang, K.-J.; Yang, W.-H.; Wang, S.-B.; Chuang, C.-H. *et al*, Band Gap Engineering of Chemical Vapor Deposited Graphene by *in Situ* BN Doping. *ACS Nano* **2013**, *7*, 1333-1341.

20. Lui, C. H.; Li, Z.; Mak, K. F.; Cappelluti, E.; Heinz, T. F., Observation of an Electrically Tunable Band Gap in Trilayer Graphene. *Nat. Phys.* **2011**, *7*, 944-947.
21. VelascoJ; JingL; BaoW; LeeY; KratzP; AjiV; BockrathM; Lau, C. N.; VarmaC; StillwellR *et al*, Transport Spectroscopy of Symmetry-Broken Insulating States in Bilayer Graphene. *Nat. Nanotechnol.* **2012**, *7*, 156-160.
22. Zou, K.; Zhang, F.; Clapp, C.; MacDonald, A. H.; Zhu, J., Transport Studies of Dual-Gated ABC and ABA Trilayer Graphene: Band Gap Opening and Band Structure Tuning in Very Large Perpendicular Electric Fields. *Nano. Lett.* **2013**, *13*, 369-373.
23. Nakaharai, S.; Iijima, T.; Ogawa, S.; Suzuki, S.; Li, S.-L.; Tsukagoshi, K.; Sato, S.; Yokoyama, N., Conduction Tuning of Graphene Based on Defect-Induced Localization. *ACS Nano* **2013**, *7*, 5694-5700.
24. Son, Y.-W.; Cohen, M. L.; Louie, S. G., Energy Gaps in Graphene Nanoribbons. *Phys. Rev. Lett.* **2006**, *97*, 216803.
25. Han, M. Y.; Å-zylmaz, B.; Zhang, Y.; Kim, P., Energy Band-Gap Engineering of Graphene Nanoribbons. *Phys. Rev. Lett.* **2007**, *98*, 206805.
26. Pan, M.; Girão, E. C.; Jia, X.; Bhaviripudi, S.; Li, Q.; Kong, J.; Meunier, V.; Dresselhaus, M. S., Topographic and Spectroscopic Characterization of Electronic Edge States in CVD Grown Graphene Nanoribbons. *Nano. Lett.* **2012**, *12*, 1928-1933.
27. Bai, J.; Duan, X.; Huang, Y., Rational Fabrication of Graphene Nanoribbons Using a Nanowire Etch Mask. *Nano. Lett.* **2009**, *9*, 2083-2087.
28. Abramova, V.; Slesarev, A. S.; Tour, J. M., Meniscus-Mask Lithography for Narrow Graphene Nanoribbons. *ACS Nano* **2013**, *7*, 6894-6898.
29. Jiao, L.; Zhang, L.; Wang, X.; Diankov, G.; Dai, H., Narrow Graphene Nanoribbons from Carbon Nanotubes. *Nature* **2009**, *458*, 877-880.
30. Kosynkin, D. V.; Higginbotham, A. L.; Sinitskii, A.; Lomeda, J. R.; Dimiev, A.; Price, B. K.; Tour, J. M., Longitudinal Unzipping of Carbon Nanotubes to Form Graphene Nanoribbons. *Nature* **2009**, *458*, 872-876.
31. Wei, D.; Xie, L.; Lee, K. K.; Hu, Z.; Tan, S.; Chen, W.; Sow, C. H.; Chen, K.; Liu, Y.; Wee, A. T. S., Controllable Unzipping for Intramolecular Junctions of Graphene Nanoribbons and Single-Walled Carbon Nanotubes. *Nat. Commun.* **2013**, *4*, 1374.
32. Xie, L.; Wang, H.; Jin, C.; Wang, X.; Jiao, L.; Suenaga, K.; Dai, H., Graphene Nanoribbons from Unzipped Carbon Nanotubes: Atomic Structures, Raman Spectroscopy, and Electrical Properties. *J. Am. Chem. Soc.* **2011**, *133*, 10394-10397.
33. Jiao, L.; Zhang, L.; Ding, L.; Liu, J.; Dai, H., Aligned Graphene Nanoribbons and Crossbars from Unzipped Carbon Nanotubes. *Nano Res.* **2010**, *3*, 387-394.
34. Wang, X.; Dai, H., Etching and Narrowing of Graphene from the Edges. *Nat. Chem.* **2010**, *2*, 661-665.
35. Wang, X.; Ouyang, Y.; Li, X.; Wang, H.; Guo, J.; Dai, H., Room-Temperature All-Semiconducting Sub-10-nm Graphene Nanoribbon Field-Effect Transistors. *Phys. Rev. Lett.* **2008**, *100*, 206803.
36. Li, X.; Wang, X.; Zhang, L.; Lee, S.; Dai, H., Chemically Derived, Ultrasoft Graphene Nanoribbon Semiconductors. *Science* **2008**, *319*, 1229-1232.
37. Cai, J.; Ruffieux, P.; Jaafar, R.; Bieri, M.; Braun, T.; Blankenburg, S.; Muoth, M.; Seitsonen, A. P.; Saleh, M.; Feng, X. *et al*, Atomically Precise Bottom-Up Fabrication of Graphene Nanoribbons. *Nature* **2010**, *466*, 470-473.
38. Ruffieux, P.; Cai, J.; Plumb, N. C.; Patthey, L.; Prezzi, D.; Ferretti, A.; Molinari, E.; Feng, X.; Mullen, K.; Pignedoli, C. A. *et al*, Electronic Structure of Atomically Precise Graphene Nanoribbons. *ACS Nano* **2012**, *6*, 6930-6935.
39. Schwab, M. G.; Narita, A.; Hernandez, Y.; Balandina, T.; Mali, K. S.; De Feyter, S.; Feng, X.; Mullen, K., Structurally Defined Graphene Nanoribbons with High Lateral Extension. *J. Am. Chem. Soc.* **2012**, *134*, 18169-18172.
40. Liang, X.; Wi, S., Transport Characteristics of Multichannel Transistors Made from Densely Aligned Sub-10 nm Half-Pitch Graphene Nanoribbons. *ACS Nano* **2012**, *6*, 9700-9710.

41. Kato, T.; Hatakeyama, R., Site- and Alignment-Controlled Growth of Graphene Nanoribbons from Nickel Nanobars. *Nat. Nanotechnol.* **2012**, *7*, 651-656.
42. Sokolov, A. N.; Yap, F. L.; Liu, N.; Kim, K.; Ci, L.; Johnson, O. B.; Wang, H.; Vosgueritchian, M.; Koh, A. L.; Chen, J. *et al*, Direct Growth of Aligned Graphitic Nanoribbons from a DNA Template by Chemical Vapour Deposition. *Nat. Commun.* **2013**, DOI:10.1038/ncomms3402.
43. Solís-Fernández, P.; Yoshida, K.; Ogawa, Y.; Tsuji, M.; Ago, H., Dense Arrays of Highly Aligned Graphene Nanoribbons Produced by Substrate-Controlled Metal-Assisted Etching of Graphene. *Adv. Mater.* **2013**, DOI: 10.1002/adma.201302619.
44. Son, J. G.; Son, M.; Moon, K.-J.; Lee, B. H.; Myoung, J.-M.; Strano, M. S.; Ham, M.-H.; Ross, C. A., Sub-10 nm Graphene Nanoribbon Array Field-Effect Transistors Fabricated by Block Copolymer Lithography. *Adv. Mater.* **2013**, *25*, 4723-4728.
45. Pan, Z.; Liu, N.; Fu, L.; Liu, Z., Wrinkle Engineering: A New Approach to Massive Graphene Nanoribbon Arrays. *J. Am. Chem. Soc.* **2011**, *133*, 17578-17581.
46. Wang, X.; Ouyang, Y.; Jiao, L.; Wang, H.; Xie, L.; Wu, J.; Guo, J.; Dai, H., Graphene Nanoribbons with Smooth Edges Behave as Quantum Wires. *Nat. Nanotechnol.* **2011**, *6*, 563-567.
47. Koch, M.; Ample, F.; Joachim, C.; Grill, L., Voltage-Dependent Conductance of a Single Graphene Nanoribbon. *Nat. Nanotechnol.* **2012**, *7*, 713-717.